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Numerical investigation of thermal responses of a composite structure in horizontally travelling fires using OpenSees

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Abstract

The traveling fire methodology provides more realistic fire scenarios for structural fire design by considering fire dynamics in large compartments which are beyond the validity or scope of conventional structural fire design codes. This novel methodology developed recently elsewhere has been implemented in the OpenSees software framework. In this work, effects of traveling fires on the thermal responses of a large composite structure are studied using OpenSees. Finite element analyses are performed to model the detailed heat transfer in the composite structure subjected to traveling fires. It is found that the traditional “equal area” concept is not applicable to evaluate the fire resistance of structures in traveling fires. Results show that traveling fires with larger sizes seem to be more detrimental to steel beams in terms of quicker failure time, while smaller traveling fires produce higher peak temperatures in the concrete slab. Large through-depth thermal gradients are created in the beam sections due to the heat sink effect of the concrete slab, with higher gradients produced by larger fires. The maximum thermal gradients in the concrete sections seem to be insensitive to the sizes of travelling fires.

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Keywords: Travelling fire; Composite structure; Thermal response; Heat transfer; OpenSees

1. Introduction

Most of the studies in the past have used codified design fires (such as the standard fires, parametric fires) for modeling the response of structures in fire. Almost all these design fires attempt to simulate the effects of post-flashover fires and inherently assume spatially uniform fire temperatures within the compartment [1, 2]. However, fire accidents have shown that in larger spaces, fires tend to travel rather than burn uniformly and simultaneously [3]. To address this problem and meet the need of structural fire design for modern structures, Rein and Stern-Gottfried et al. [3-5] have developed a novel methodology which represents traveling fires more realistically by including key aspects of fire dynamics in large compartments. This methodology would normally require detailed thermal and structural modeling in order to quantify the actual response of structures to fire. In this work, it has been implemented in the OpenSees framework [6] which has been extended by the authors of this paper to include “structures in fire” analysis capability [7, 8]. New capabilities of the extended OpenSees framework include heat transfer modeling of structural members with fire imposed boundary conditions and thermal-mechanical modeling using beam or shell elements [7, 8]. It is then used to investigate thermal responses of a fictitious composite structure subjected to a range of horizontally traveling fires. Key findings on thermal response and their implications on subsequent structural performance will be discussed in this paper.

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2. The traveling fire methodology

In the traveling fire methodology, the fuel is normally assumed to be uniformly distributed across the whole floor plate with a fire load density q_f (MJ/m²). Assuming the fire burns with an area of A_f (m²) and a constant heat release rate per unit area \dot{Q}'' (kW/m²), this corresponds to a power \dot{Q} (kW) for this particular size of fire. Each fire area would have a constant burning time t_b , which is given by [3, 4]

$$t_b = \frac{q_f}{\dot{Q}''} \quad (1)$$

Note that t_b is a characteristic burning time of the near field, and is determined by fuel load density and the properties of the fuel but independent of fire sizes.

Assuming the fire has a length of L_f along its travelling direction, the travelling speed s (m/s) is characterized by [3]

$$s = \frac{L_f}{t_b} \quad (2)$$

According to Eq. (1) and (2), larger fires would have longer L_f and travel faster. The floor area where the fire has traveled across is deemed to be burnt out. The fire environment is divided into two horizontal regions with reference to the fire source, “near field” and “far field”, at any time interval as the fire travels. In the near field, a constant fire temperature of 1200 °C is normally assumed [3-5]. In the far-field, the temperature of the fire environment is determined by the hot smoke moving away from the fire source. The Alpert correlation has been used to calculate the far-field temperature [3-5, 9]

$$T_{\max} - T_{\infty} = \frac{5.38(\dot{Q}/r)^{2/3}}{H} \quad (3)$$

where T_{\max} is the maximum temperature in the ceiling jet, T_{∞} is the ambient temperature, \dot{Q} is the heat release rate of the fire, r is the distance from the fire center, H is the floor height.

3. Case study of a composite structure

3.1. The structure

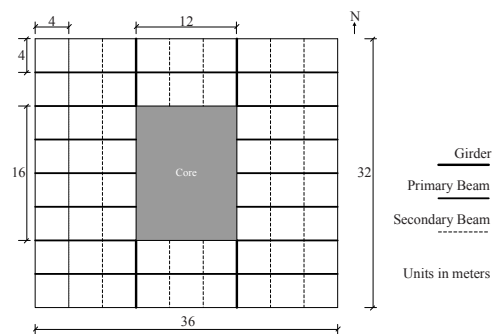


Fig. 1. Schematic plan view of the structure.

The structural layout examined in this paper is a generic modern tall building with a floor height of 4 m. The typical floor plan is shown in Fig. 1, which could possibly produce fire propagation similar in form to that of the WTC towers [10]. The dimensions of the beams are selected according to preliminary design criteria. These are UB 533 × 210 × 122 for the girders, UB 406 × 140 × 39 for the primary beams and UB 356 × 171 × 51 for the secondary beams. The floor area A_{total} is 1152 m²,

with a core of 192 m². The presence of core is important to structural behavior and should be taken into account when performing structural analysis. However, it is a reasonable approximation to neglect the core when calculating the fire temperatures [3].

3.2. The traveling fire scenarios

The building is assumed to be used for office purpose and the fuel is uniformly distributed on the floor plate with a characteristic fire load density of 420 MJ/m² as given in [2]. Mass burning rate of typical office fuels is reported in the range of 20–40 g/m²s [11], which suggests that the heat release rate per unit area would range from 320 to 640 kW/m² if we assume a typical heat of combustion of 16 kJ/g for cellulose fuels [1]. An average value of 480 kW/m² is taken in this work.

It is assumed that the fire travels in a linear path from the west to the east of the floor and extends the whole width of the building, which is similar to the treatment used in [3, 5]. The initial length of the fire is $L_0 = 0.1$ m, and then it maintains a constant length L_f once the fire has grown to the specified size A_f

$$L_f = \frac{A_f}{W} \quad (4)$$

For this linearly traveling fire, the total burning time is calculated by the following equation [3]

$$t_{total} = t_b \left(\frac{L - L_0}{L_f} + 1 \right) \quad (5)$$

The size of fire is a major variable in the traveling fire methodology, which balances the far field temperature and the total burning time [3-5]. In this work, the fires are varied from 4% to 42% of the floor area. Other parameters associated with the fire size are summarized in Table 1.

Table 1. Summary of the fire scenarios

A_f (m ²)	Fire size	L_f (m) (Eq. (4))	\dot{Q} (MW)	t_{total} (min) (Eq. (5))	s (m/min) (Eq. (2))
48	4%	1.5	23.04	364.0	0.1
96	8%	3	46.08	189.3	0.2
192	17%	6	92.16	102.0	0.4
288	25%	9	138.24	72.8	0.6
384	33%	12	184.32	58.3	0.8
480	42%	15	230.4	49.5	1.0

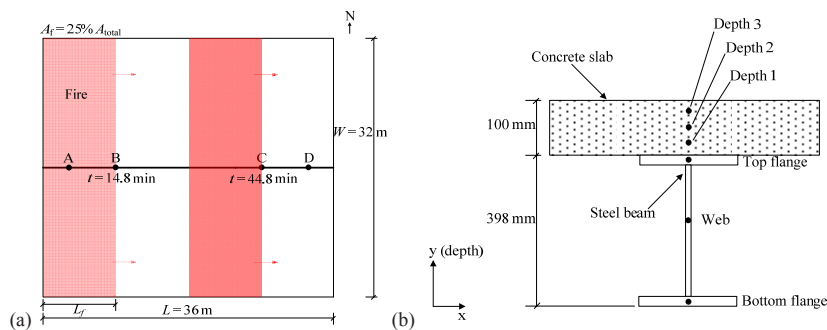


Fig. 2. Schematic of (a) the linearly traveling fire across the floor plate (b) the composite section.

The temperature distribution in the composite floor (on top of the ceiling of the fire compartment) along the longest direction will be examined, as the structure along this direction is more susceptible to stability issues in case of a fire. Fig. 2

shows a linear traveling fire and four locations (A, B, C, D) for temperature analysis across the floor. The schematic of the composite section and corresponding temperature locations on the section are also indicated in Fig. 2.

3.3. Heat transfer modeling

The recently developed fire and heat transfer modules in OpenSees [7, 8] are used in this work to calculate the transient temperature rise in the composite structure. As a result of the traveling fires, the heat transfer in the composite floor could have a fully three dimensional character; however, we have chosen to ignore heat conduction along the direction of fire propagation to simplify the problem and reduce the computational expense. Furthermore, the rate of heat conduction along that direction could be much slower than the fire traveling speed [3]. Hence two dimensional heat transfer analyses are carried out for separate sections at the locations (A, B, C, D) specified in Fig. 2. This approach is justified by Franssen et al. [12], who showed that even if a steel member is subject to highly localized heating conditions, a series of separate two dimensional heat transfer analyses represent fully three dimensional heat transfer analyses with adequate accuracy.

The 0.9 mm thick metal deck between the steel beam and the concrete slab is included in the finite element model. The temperature-dependent material properties of concrete (with a moisture level of 1.5%) and steel are taken from [13] and [14] respectively. The top of the concrete slab is assumed to be exposed to ambient environment of 20 °C. The bottom surface of the slab and three sides of the beam are exposed to the thermal environment generated by the traveling fires. The convection coefficients for fire-exposed surfaces and unexposed surfaces are taken as 25 W/m² K and 4 W/m² K respectively [2]. An emissivity of 0.7 is specified for both the concrete and steel according to [13].

4. Results and discussions

For composite members in fire, the thermal response affects significantly the structural response. Significant information on the structural behavior under thermal effects has been gained based on the Cardington tests over the previous years [15]. Composite floors are designed for flexure but also carry loads through a compressive and tensile membrane action. During the heating phase, the composite section experiences a mean temperature rise which leads to overall compression in a laterally restrained member. It also experiences a thermal gradient over the depth of the section which leads to a uniform hogging moment along the length of a rotationally restrained member (which is usually the case at least at low temperatures). The hogging moment also causes compression forces in the bottom flange of the steel beam.

4.1. Temperature rise

Typical fire temperatures and the temperature histories of the beam and concrete slabs are shown in Fig. 3, which is shown for a medium size fire (25% of the floor area). As the fire travels across the length of the floor plate, each of the locations (A, B, C, D) experiences sequentially the initial far-field heating prior to the arrival of flaming region, near-field heating, the posterior far-field heating, and then cooling to the ambient (20 °C). The arrival time of near-field at each location is dependent on both the traveling speed and the distance from the fire origin. Therefore, the traveling fire produces spatially and temporally varying heating conditions across the floor, which cannot be naturally addressed by conventional design fires such as the parametric fire curves as given in EC1 [2].

It is interesting to note that the fire curves are symmetric for the geometrically symmetric locations (A and D, B and C). This is because that the far field temperature is a function of relative distance to the fire center as given in Eq. (3). Note, according to the “equal area hypothesis” [1], the fire severity at location A (63 mins) and location D (72 mins) would be the same due to identical areas under the two fire curves (above a reference temperature of 300 °C). However, temperatures in the beam at location D (72 mins) are up to 100% higher than the corresponding values at location A (63 mins), while temperatures in the slab (depth 3) at location A (63 mins) are up to 43% higher than those at location D (72 mins). Similar results are also found for other traveling fire scenarios in this work. This clearly goes against the traditional measure of fire severity in terms of the “equal area” concept which links fire severity to the area under the temperature-time curve [1].

The peak temperatures at the bottom flange and center of the web reach 1200 °C in all the cases, although peak values for the top flange are slightly lower. Therefore, the time taken to reach a critical temperature seems to be a more meaningful parameter for the investigation here, as unprotected steel members may fail rapidly in fires [1]. The critical temperature is taken as 550 °C as this value is often used as a simple failure criterion for steel members [1]. As shown in Fig. 4, it takes shorter time for the beam to reach the critical temperature when exposed to larger fires. This is expected as larger fires travel faster and lead to earlier arrival of the near-field heating. It takes slightly longer for the top flange to reach 550 °C due to the heat sink effect of the concrete slab. As pointed out by Stern-Gottfried [3], the time to reach a specified temperature can depend on the distance relative to the fire origin. Location A has the shortest distance to the initial fire location and it is the

earliest to experience the near field heating. Therefore, the steel beam there suffers the most detrimental heating conditions compared to other locations, which reaches 550 °C within 2.5 mins for the 42% fire size, corresponding to a heating rate of 220 °C/min. However, it should be noted that global structural fire performance is not simply determined by local critical temperatures, and mechanical interactions between structural members need to be considered as well.

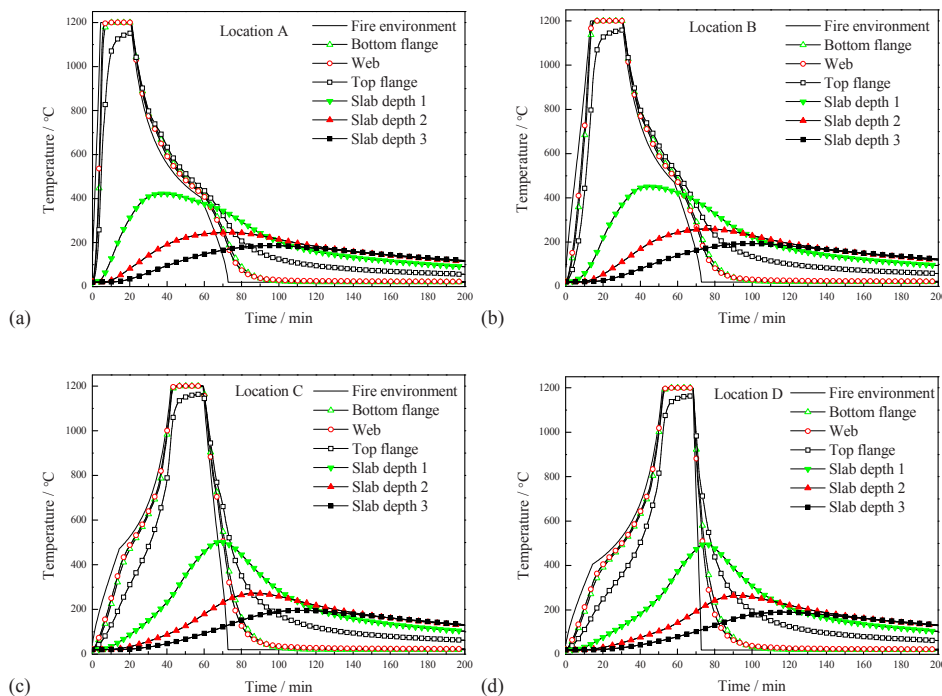


Fig. 3. Temperature rise in the composite section subjected to traveling fire (25% fire size) at location (a) A (b) B (c) C (d) D.

Figure 5 shows the variations of peak temperatures in the concrete slab. As shown in the figure, smaller fires such as 4% and 8% fires produce the highest temperatures at every location. This is due to the fact that smaller fires produce lower far-field temperature but burn for much longer time. As given in Table 1, the total burning time for the 4% fire is about 7 times as that for the 42% fire. Plus concrete has very low thermal conductivity, which means more heat would penetrate through the concrete slab subjected to smaller traveling fires. Similar results are also found by Law et al. [5], who suggested that smaller fires (10%–20%) represent an optimum heating balance between far-field temperature and far-field heating duration. Therefore, in light of peak temperature reached in the concrete slab, the 4% fire would be the most onerous in the current case study. It is also noted that peak values increase with the distance away from fire origin, as temperatures in Fig. 5(c) and (d) are generally higher than the corresponding values in Fig. 5(a) and (b). This is also seen in previous studies for concrete structures [3, 5]. Similar to what we discussed above, this is because that further locations experience a relatively long period of far-field heating prior to the arrival of near-field as shown in Fig. 3.

4.2. Through-depth thermal gradient

As mentioned at the beginning of this section, thermal gradient through the depth of the composite floor plays an important role in determining the structural behavior of composite structures. This section examines the effect of traveling fires on the thermal gradients in composite sections at different locations across the floor plate.

Figure 6 shows the through-depth temperature profiles in the steel section at the four locations, from which the thermal gradients can be easily identified. Each single curve in these figures represents the maximum through-depth thermal gradient in the course of temperature development in the beam section for a specific fire scenario. It is noted that the temperature does not strictly follow a linear distribution across the whole section depth. Temperatures at the bottom flange and the middle point of web are relatively close, with values in the web slightly higher. This is because that the web is usually slightly thinner than the flange. Larger gradients appear between the middle of the web and the top flange. It seems that heat sink effect of the concrete slab has an appreciable effect on the thermal gradient in the beam section, with

temperatures in the top flange up to 400 °C lower than those in the web. This through-depth temperature profile indicates that using a uniform temperature distribution or a uniform thermal gradient for the whole beam section may not be realistic. Incorporating this thermal gradient can have significant influence in modeling steel beams in fire [16].

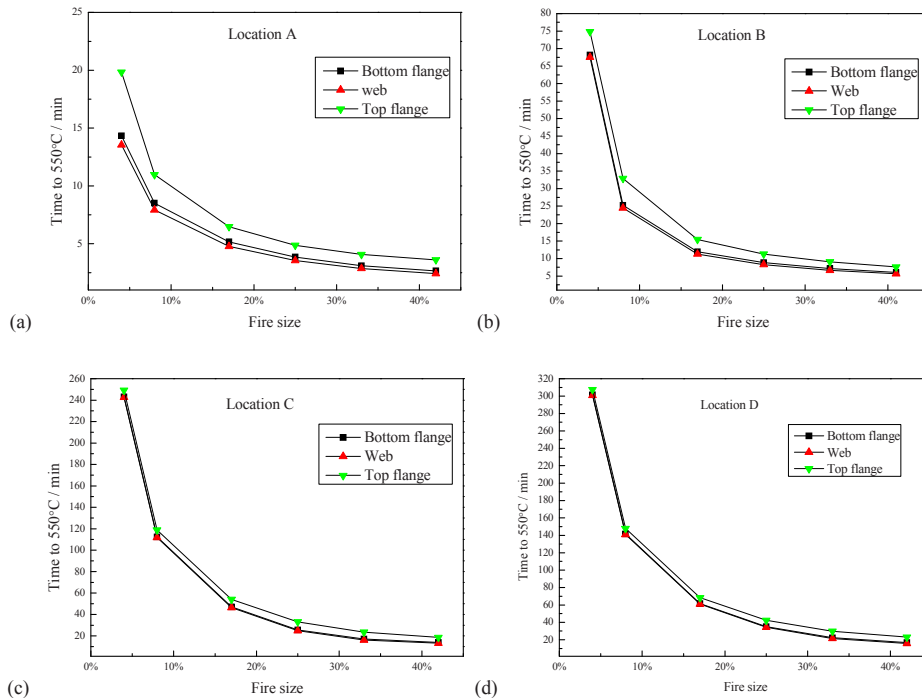


Fig. 4. Time taken to reach reference temperature at location (a) A (b) B (c) C (d) D.

Figure 6 also shows that larger fires (25–42%) produce greater thermal gradients than smaller fires at all of the four locations. This is because larger fires generate higher far-field temperatures and travel faster across the floor plate. Besides, they have shorter burning durations and thereby structural members are subjected to more intensive heating within shorter time. The results are similar to those found in the study of effects of “long-cool” and “short-hot” parametric fires [17]. Fire sizes greater than 25% produce nearly identical thermal gradients. The gradients generally decrease with the distance from the fire origin, which makes sense as beams at further locations experience longer and less rapid initial far-field heating.

Figure 7 shows the maximum thermal gradients in the concrete slab at different locations across the floor. Unlike the peak concrete temperatures, gradients in the concrete slab seem to be insensitive to the fire sizes and locations. Large gradients (9.9–10.7 °C/mm) are developed within shallower regions of the slab, while smaller gradients (3.4–4.6 °C/mm) are found in deeper regions. This range of high gradients seems to be more severe than the values found in existing work using conventional parametric fires [17]. The results also suggest that the maximum contribution to the deflections of slabs from thermal bowing should be similar at different locations and for different fire sizes. This further suggests that the concrete slab will have similar structural behavior in traveling fires independent of the location and fire size. However, as Fig. 7 gives the maximum thermal gradients at each location, time to reach these maximum gradients should be different for each case. Larger fire sizes and thus earlier arrival of the near-field could cause less time to reach maximum gradient.

It should be noted that the largest contribution to the thermal gradient in a composite section comes from the difference in mean temperatures between in the steel beam and concrete slab. In terms of its structural effect it can be an order of magnitude larger than the gradients within the beam or the slab on their own.

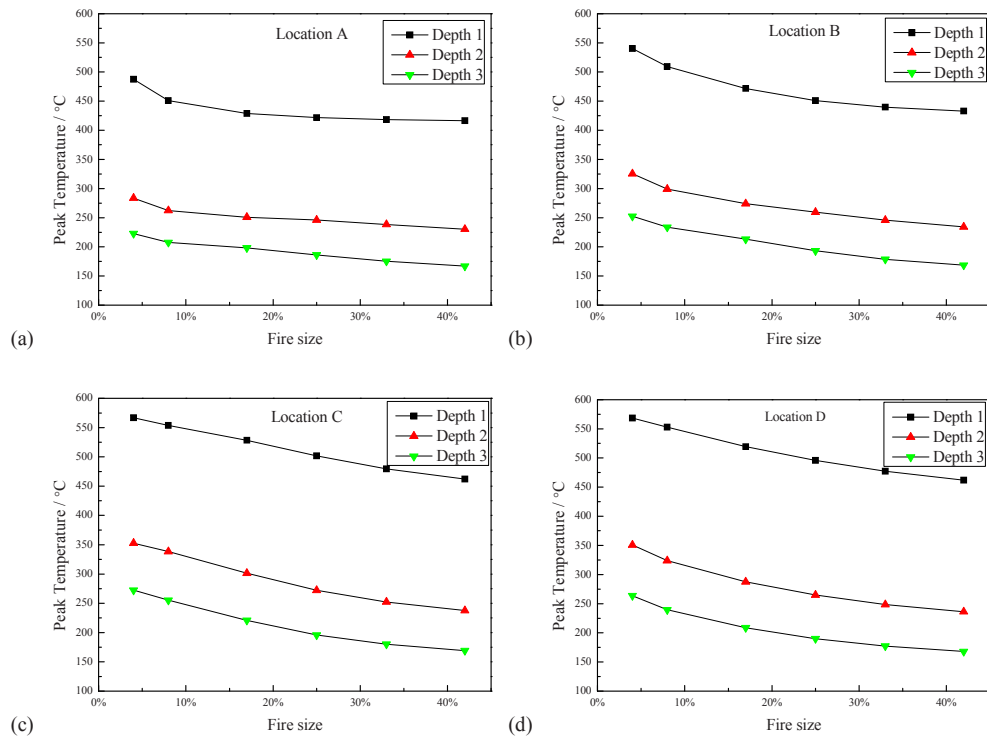


Fig. 5. Peak temperature of the concrete slab at location (a) A (b) B (c) C (d) D.

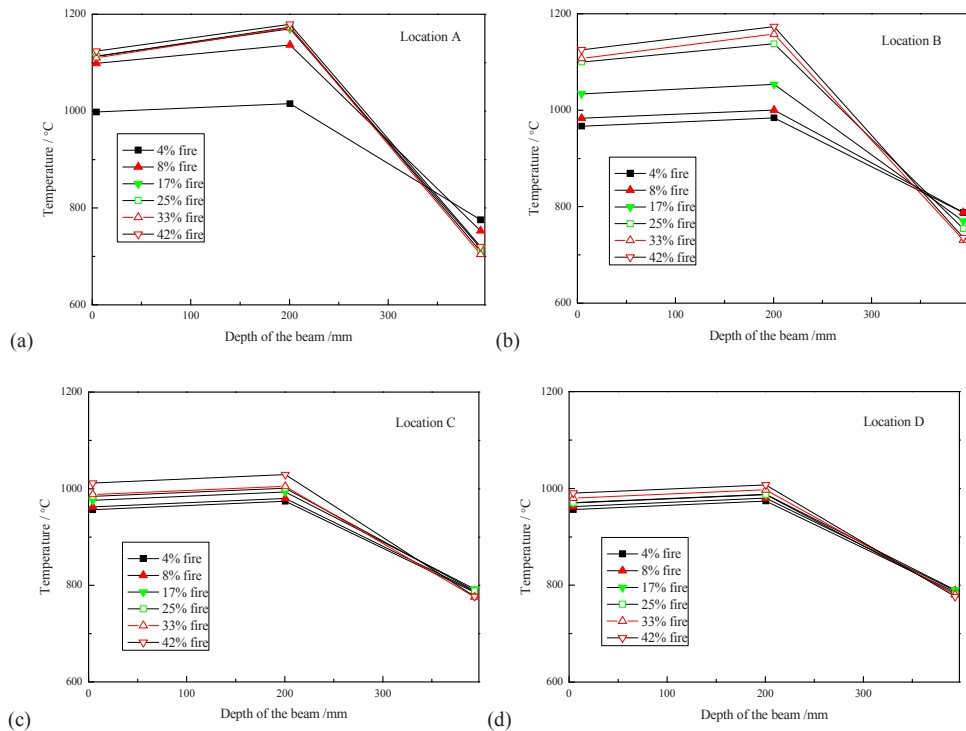


Fig. 6. Through-depth temperature profile for the beam at location (a) A (b) B (c) C (d) D.

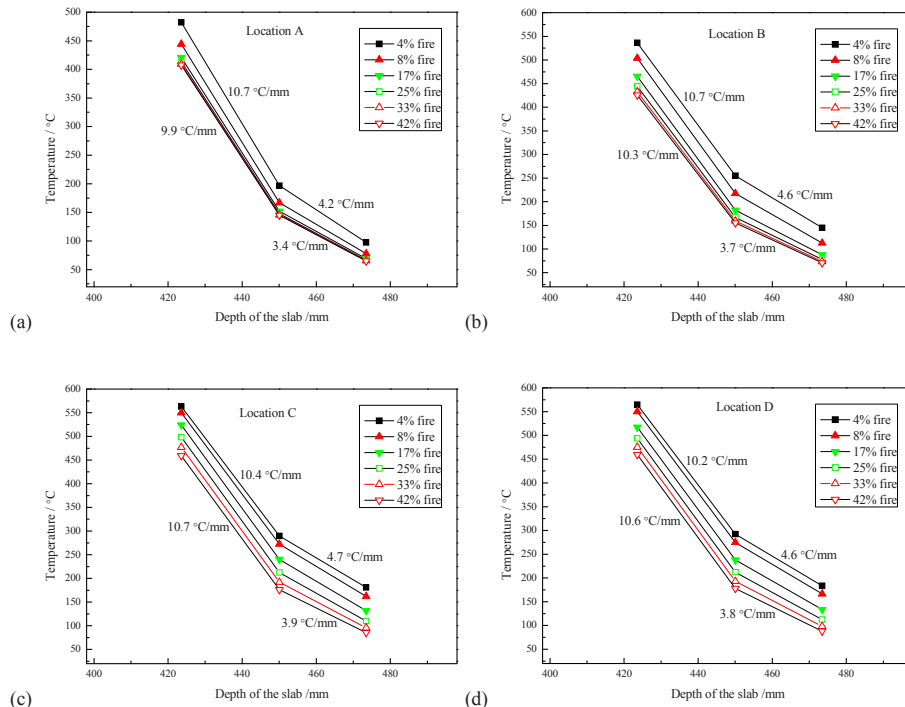


Fig. 7. Through-depth temperature profile in the slab at location (a) A (b) B (c) C (d) D.

5. Conclusions

The traveling fire methodology for structural fire design has been implemented in the OpenSees software framework. A case study has been carried out to examine the thermal responses of a composite structure in traveling fires. The following are some of the major findings: (1) Traditional thinking of fire severity in light of “equal area” concept seems to be invalid for traveling fires. Fire temperature curves at symmetric locations were supposed to have identical fire severity according to the “equal area hypothesis” but lead to temperature differences up to 100% at these locations in the composite floor. (2) Traveling fires with larger sizes lead to lower times to reach critical steel temperature. (3) Traveling fires with smaller size produces higher peak temperatures in the concrete slab. (4) Thermal gradients in the beam are created due to the presence of concrete slab. Larger size fires produce higher through-depth thermal gradients in the composite section. (5) Maximum thermal gradients in the concrete slab seem to be insensitive to locations and sizes of travelling fires.

Finally, this work also show the capability of OpenSees as a platform to perform advanced structural fire analysis by integrating fire, heat transfer and structural models. Results on structural analysis will be presented in future work.

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